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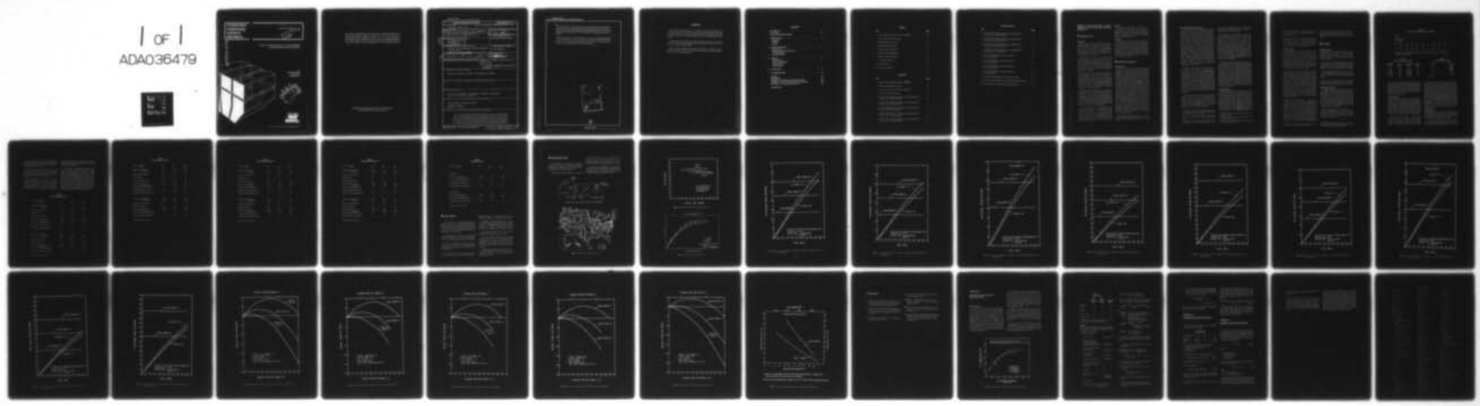

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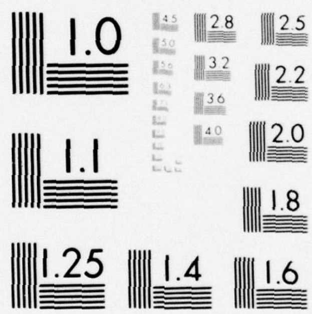

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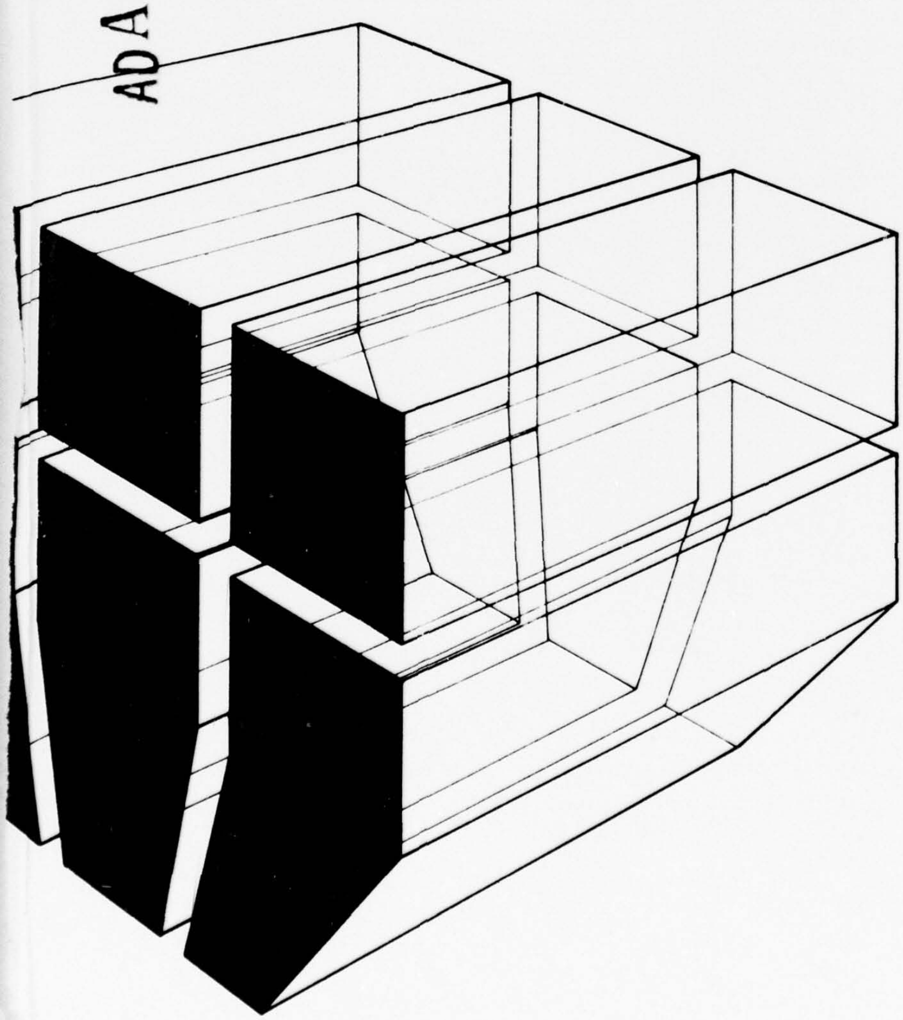
MARKET EVALUATION STUDY: SOLAR DOMESTIC WATER HEATERS FOR DOD BARRACKS



by
Larry Windingland
George Walton
Douglas Hittle

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This study assesses the potential market for solar domestic hot water systems in DOD bachelor enlisted and bachelor officer quarters (barracks). The number and locations of existing and planned bachelor enlisted and bachelor officer quarters in the United States are analyzed, and the locations where solar domestic water heating is most feasible are determined. Life-cycle costs of providing solar domestic water heating systems are analyzed and the DOD market potential for these systems determined for varying system costs.

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The results of more than 120 one-year solar hot water heating system simulations are presented along with a dimensionless graph and methodology which can be used to estimate solar hot water heater performance for building loads and sites other than those studied. The potential markets for solar collectors based on varying system costs are presented.

Results indicate that at an anticipated future system cost of $9/sq ft ($97/m²) of collector the probable market for solar collectors is 4.4 million sq ft (409 000 m²). Over a 20-year life, the potential savings resulting from application of this collector area is estimated to be 4.5 million barrels of fuel and $29 million.

sq m
sq m

FOREWORD

This study was performed by the U. S. Army Construction Engineering Research Laboratory (CERL) for the Federal Energy Administration (FEA) under Project Order No. CG-05-50083-00. The research was conducted by the Energy Branch of the Energy and Power Division. Mr. L. Keller, DAEN-FEU-A, was the Technical Monitor for the project.

The assistance of the U. S. Army Facilities Engineering Support Agency, Fort Belvoir, VA, in performing the DOD building inventory and of Mr. John Grgas, CERL, in the life-cycle cost analysis is acknowledged.

COL J. E. Hays is Commander and Director of CERL and Dr. L. R. Shaffer is Technical Director. Dr. D. J. Leverenz is Chief of the Energy Branch and Mr. R. G. Donaghy is Chief of the Energy and Power Division.

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MARKET EVALUATION STUDY: SOLAR DOMESTIC WATER HEATERS FOR DOD BARRACKS

1 INTRODUCTION

Background

Like all energy users, the Federal government is faced with rapidly increasing energy costs and, in some locations, shortage or curtailment of its energy supplies. Thus, it is searching for a new and abundant natural energy source. Because of its abundance, widespread distribution, and absence of recurring fuel cost, solar energy may be an ideal source.

The technical feasibility of using solar energy gathered by flat-plate collectors for hot water and space heating has been established both in theory and practice. Although the design phase may be somewhat more complex, the installation phase requires little more skill than is required to install conventional systems. Thus, the major consideration in solar system application is economics.

The high initial cost of solar system components is the major barrier to economic use of large-scale solar system application. Initial cost is high because at present, most solar system components are practically hand-built. The market demand for these systems has not been large enough to encourage the capital expenditures necessary to promote full application of automated production techniques, which would significantly reduce the cost of solar components.

Since solar energy could play such an important role in providing for future energy needs within the United States, the Federal Energy Administration (FEA) is developing a comprehensive plan which will provide a substantial initial solar component demand through economically justified applications on Federally owned buildings. This demand is expected to encourage the use of automated production techniques, thereby lowering the first cost of solar components.

Since the Department of Defense (DOD) owns approximately 80 percent of the buildings controlled by the Federal government, it is the greatest single potential government user of solar systems. As a first step in determining the overall DOD market, the market potential for solar domestic hot water heating in DOD bachelor enlisted and bachelor officer quarters (barracks) was examined.

Objective

The objective of this project was to assess the market potential for solar domestic water heaters in existing and proposed barracks by determining the number of solar collectors which could be economically applied on the buildings, based on various estimated installed system life-cycle costs.

Approach

A real property inventory of existing and planned barracks within the United States was performed to determine the number of barracks where solar domestic water heaters could be used. A solar domestic hot water system was chosen and modeled and computer simulations of this system were used to determine its performance. A life-cycle cost analysis of the system was performed, and a market potential was established based on economic viability.

2 METHOD OF ANALYSIS

Building Survey

The Army, Air Force, and Navy (Marine Corps property is included in Navy property) maintain computerized real property inventories which list buildings by category. These inventories include the location, date acquired, number of square feet, type of construction, and in the case of quarters, number of men per building. These inventories were used to determine the number of existing and planned bachelor enlisted and officer quarters (BEQ/BOQ) on DOD installations where solar domestic water heaters could be used. To limit the inventory to structures most amenable to solar domestic water heating equipment, only buildings of permanent construction less than 20 years old were chosen; this insured structural adequacy and useful economic life. In addition, only buildings having reasonably flat roofs were chosen, thus facilitating installation of solar collecting equipment. The information gathered about each structure was the number of persons housed, the number of square feet of roof area per person, the capacity of the existing hot water heater, and the energy source presently used. This inventory was performed by the Facilities Engineering Support Agency (FESA).[1] Pertinent data have been extracted from the FESA report for use in this report.

[1] Gary Stewart, *Solar Domestic Water Heaters in DOD Buildings*, Technical Report FESA-RT-2004 (U. S. Army Facilities Engineering Support Agency [FESA], September 1975.)

Solar System Performance Evaluation

The solar domestic hot water heating system shown in Figure 1 was chosen as the most logical approach for retrofitting existing barracks and for new barracks installations. Solar energy falling on the collectors heats the collector plates and thus the water circulating through the collector. The pumps in the system operate whenever temperature of the fluid leaving the collector exceeds the temperature of the water in the top of the storage tank. The heat from the collector fluid is transferred to a storage tank through a counterflow heat exchanger. An auxiliary heater is used to maintain the water in the auxiliary storage tank at 140°F (60°C) during periods of low solar insolation. In addition, to conserve hot water, a cold water mixing valve was added to the system to lower the tank exit water temperature whenever the solar energy provides water at a temperature exceeding 140°F (60°C). A computer simulation model of the system was developed to study its performance at four selected sites using actual weather tapes.

The collector was modeled as a single cover, flat-plate collector with a selective surface (absorptivity = .90, emissivity = .10) using the Hottel-Whillier-Bliss[2] zero-capacitance steady-state equation. The collector thermal loss coefficient was computed using Klein's[3] experimentally derived equations which account for the effects of the number of glass covers, collector tilt, collector plate emissivity, wind speed, ambient temperature, and collector fluid temperature. The angular transmittance of the cover was included in the model. All simulation runs were performed assuming a single-cover selective surface collector. (Appendix A presents results of simulation runs using different collector parameters.)

Collector fluid was a 40 percent glycol and water mixture. The three types of solar radiation—beam, diffuse from sky, and diffuse reflected from the ground—were proportioned based on the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE)[4] clear sky coefficient applied to radiation on a horizontal surface.

[2]R. W. Bliss, "The Derivation of Several Plate Efficiency Factors Useful in the Design of Flat-Plate Solar Heat Collectors," *Solar Energy*, Vol 3, No. 4 (1959).

[3]S. A. Klein, "Calculation of Flat-Plate Collector Loss Coefficients," International Solar Energy Society Meeting (1974).

[4]*Handbook of Fundamentals* (American Society of Heating, Refrigeration and Air Conditioning Engineers, 1972).

The heat exchanger between the collector and storage tank was modeled in terms of its effectiveness; an effectiveness of 0.8 was used.

The storage tank was modeled as a cylinder with a height-to-diameter ratio of 2. It was assumed to be insulated with the equivalent of 3 in. (7.62 cm) of fiberglass (U = .12). The tank was assumed to be stratified (three layers), since the typical barracks demand profile is assumed to have a low flow rate from storage during solar collection hours; i.e., most demand occurs during early morning and late evening. The auxiliary heater was modeled as a standard domestic hot water heating tank with the equivalent of 1 in. (2.54 cm) of fiberglass (U = .37). Energy losses from the tanks were based on thermal conductance from the tanks to the surroundings, assuming that the tanks were located in the building.

To determine optimum system performance, computer simulations were performed for various individual system parameters for the four regions of the United States (Figure 2). The regions were based on the amount of annual solar insolation (daily average) reaching the surface.[5] The regions were defined by state boundaries so military population data (available by state) from the survey could be used in the market analysis. The sites chosen in each region for the simulation were Los Angeles, CA; Charleston, SC; Columbia, MO; and Madison, WI. Actual weather tapes from these sites were obtained. The results of these simulations provided the solar system performance parameters used in the economic analysis.

Load Determination

Information on size of water heaters and their fuel source is available only at base level. Even at this level, however, consumption data were not available. Since time did not permit a base-by-base search for these data, DOD design criteria and commercially measured data from similar buildings were evaluated to determine the hot water demand to be used. The DOD method for hot water heating design (Appendix B) estimates usage of 30 to 40 gal (0.11 to 0.15 m^3) per day per person. The ASHRAE Handbook and Product Directory[6] and the Piping Handbook[7] give

[5]*Climatic Atlas of the United States* (U. S. Department of Commerce, June 1968).

[6]*ASHRAE Handbook and Product Dictionary, 1973 Systems* (1973), pp 37.11 - 37.17.

[7]S. Crocker and R. King, *Piping Handbook*, fifth edition (McGraw-Hill, 1967), p 23-18.

actual consumption data for college dormitories of 13 to 22 gal (0.05 to 0.08 m^3) per day per person of 140°F (60°C) water.

Because it was felt that measured data would be more consistent with actual usage and that dormitories should reasonably approximate barracks, the solar simulation model was run with a consumption rate of 20 gal (0.075 m^3) per day per person.

Economic Analysis

Costing guidelines provided by the Office of the Chief of Engineers[8] and coordinated with the FEA were used to determine the life-cycle costs of providing solar systems in each region, based on the results of the simulation study. The solar collector area that could be economically justified for each system cost in each region was analyzed using two methods—most economical (least life-cycle cost), and most fuel saved (life-cycle system costs equal fuel savings). Appendix C presents the equations used in the analysis.

The economic analysis was based on an expected 20-year system life and fuel costs equivalent to $2.50 per million Btu ($2.37/GJ) (approximately $.35/gal). The fuel costs were based on No. 2 fuel oil prices, since this cost is relatively stable throughout the country and other competing fuels (with the exception of electricity) are believed to seek and eventually reach the energy-equivalent price of fuel oil. A 10 percent fuel escalation rate was assumed through 1980 with a 4 percent annual escalation rate from 1981 to 1996. To provide a base for the economic analysis, it was assumed that the solar systems would be purchased and installed in 1976. At the suggestion of the Federal Energy Administration, the DOD time value of money assumed in the analysis was 6.5 percent.

Because of the unavailability of operating and maintenance (O & M) costs for solar systems, it was assumed that the present value of the total O & M costs would be included in the various total system costs analyzed. It was also assumed that installed total system costs could be computed on a square foot of solar collector area basis; this assumption should be valid for the size of systems contemplated. Installed solar domestic water heating system costs of $9/sq ft, $15/sq ft, and $20/sq ft ($97/m^2, $161/$m^2$ and $215/$m^2$) were considered. Based on these assumptions, solar domestic water heating is economically justified where the present worth of fuel costs over the 20-year life exceeds the installed cost of the solar system. Market projections were made based on the economic analysis.

[8]Telephone communication from Wade Sato, Office of the Chief of Engineers, DAEN-MCE-U, 2 July 1975.

3 FINDINGS

Building Inventory[9]

Investigation of four Army posts indicated that sufficient roof area is available for collectors of a solar domestic water heating system on most barracks. Possible exceptions are high-rise buildings exceeding eight stories (Table 1).

Observations at various DOD installations indicated that the pitch of roofs on most DOD barracks facilities is small enough to facilitate solar collector mounting and will not create a serious problem in installation.

Table 2 groups DOD barracks by occupancy. There is no really predominant size among the large number of barracks that can be used for standardized system design.

Table 3 shows the approximate number of personnel housed in barracks in each region. The distribution shown in Table 2 was assumed to exist in each region.

Solar System Simulation

To determine solar system performance, the simulation program was run for a typical 100-man barracks building with an annual load of 20 gal (0.075 m^3) of 140°F (60°C) water per person per day. Full-year simulations were run for each site using a wide range of collector tilt angles. Although collector tilt angle is not critical, the optimum angle for solar domestic hot water heating (most energy gained over the entire year) was found to be equivalent to the latitude of the installation location (Figure 3).

Full-year simulations were then run using a variety of collector areas and different storage volumes at the optimum tilt angle. For each collector area, the optimum total hot water storage volume was roughly equivalent to 1 day's usage.

[9]Data in this section were extracted from Gary Stewart, *Solar Domestic Water Heaters in DOD Buildings*, Technical Report FESA-RT-2004 (FESA, September 1975).

Table 1
Roof Area Per Man for Barracks at Four Installations*

No. Floors	1	2	3	4	5	6	7	8	9
Roof area per man in sq ft (m^2)									
BOQ	478 (44.4)	239 (22.2)	159 (14.8)	119 (11.1)	95 (8.8)	79 (7.3)	68 (6.3)	59 (5.5)	53 (4.9)
BEQ	187 (17.4)	93 (8.6)	62 (5.8)	46 (4.3)	37 (3.4)	31 (2.9)	26 (2.4)	23 (2.1)	20 (1.9)

*Areas are averages calculated from existing quarters at Fort Dix, NJ; Fort Belvoir, VA; Fort Leonard Wood, MO; and Fort Bliss, TX.

Table 2
Barracks Distribution by Occupancy

No. Persons Housed	No. Buildings	No. Persons Housed	No. Buildings
1-25	805	151-175	175
26-50	875	176-200	90
51-75	200	201-250	225
76-100	155	251-300	90
101-125	125	301-400	125
126-150	540	Over 400	115

Table 3
Barracks Occupancy by Region

Region*	No. Personnel
I	108,000
II	108,000
III	98,000
IV	63,000
Total	377,000

*See Figure 2.

The results of the simulations run for each location (Figure 4) also provided a universal curve which can be used with reasonable accuracy at any location to determine the collector area required to satisfy a particular percentage of hot water heating load. Appendix A presents the universal curve and a description of how it was derived and can be used.

Economic Analysis

Since the building inventory showed a large variance in possible sizes for barracks solar system application and the hot water heating load is linear in respect to population, the economic analysis used the performance data normalized to a per-man equivalent. The results of the economic analysis were plotted to show the payback period in years of various solar system sizes for each of the three solar system costs. Figures 5 through 13 show dollar savings per barracks occupant.

These figures were consolidate[illegible] show the variation in estimated savings occur[illegible] over the 20-year system life as a function of collector area per occupant (Figures 14 through 17). Figure 18 shows similar curves for one location, based on a 10 percent time value of money, rather than 6.5 percent. The peaks of these curves show the most economical collector area (greatest dollar savings) per occupant at each site for each system cost. Points to the right of the curve produce greater fuel savings but lower actual dollar savings. The intersections of the curves and the zero savings axis show the collector areas that save the most fuel while still recovering the capital investment in 20 years. These curves indicate that, given the assumptions of this study, employing flat-plate collectors to utilize solar energy for a portion of domestic water heating requirements is economically feasible in all areas studied. The proper mix of solar and conventional, however, must be used to optimize the system at a particular location.

Market Analysis

Market projections for solar hot water heating in DOD barracks were made for each region. However, in considering the projections, the assumptions made in the analysis *must* be kept clearly in mind:

1. Solar hot water system costs vary linearly with collector area. (This assumption, though not valid for very small systems, improves as system size increases.)

2. The system costs used are present value costs, including collectors, pumps, piping, tanks, installation, and annual O & M cost; they should therefore not be construed as collector costs alone.

3. System load used is 20 gal (0.075 m^3) of hot water per day per man. (The market projections can be scaled linearly if future consumption measurements show the actual system load to be different.)

The optimum collector area (apex of curve) and break-even collector area (zero cost crossover point) were taken from Figures 14 through 17 and applied to the regional population data. Tables 4 through 7, which show the results of this analysis for each region, also show the percent of solar energy used in satisfying the load and the estimated dollar and fuel savings possible if the potential market amount of collector area were fully implemented.

To determine the total market potential for solar hot water heaters in DOD barracks, the regional markets were summed (Table 8). Figure 19, which shows the estimated potential solar collector market for water heating in DOD barracks for various system costs, indicates that the market potential is extremely sensitive to system costs. It must be remembered that the market potentials indicated on the tables and figures are estimates only, and that firm figures must be obtained from individual barracks assessments using the present value of life-cycle costs of the particular system size for the actual barracks location.

Table 4
Market Potential for Region 1*

System Cost ($/sq ft)	9	15	20
($/$m^2$)	97	161	215
Optimum Area (sq ft/person)	12	7	3
(m^2/person)	1.11	0.65	0.28
Solar Energy Contribution (%)	75	52	26
Savings ($/person)	90	35	10
Savings (barrels fuel/person)	13.1	9.1	4.6
Market Potential (sq ft x 10^6)	1.30	0.76	0.32
(m^2 x 10^5)	1.20	0.71	0.30
(for entire region 108,000 personnel)			
Potential Dollar Savings (millions)	9.7	3.8	1.1
Potential Fuel Savings (million barrels)	1.4	1.0	0.5
Break-Even Area (sq ft/person)	24.5	14.5	6.5
(m^2/person)	2.28	1.35	0.61
Solar Energy Contribution (%)	88	78	49
Savings (barrels/person)	15.3	13.6	8.6
Market Potential (sq ft x 10^6)	2.64	1.57	0.70
(m^2 x 10^5)	2.45	1.46	0.65
(for entire region 108,000 personnel)			
Potential Fuel Savings (million barrels)	1.7	1.5	0.9

*Figures based on a 20-year life.

Table 5
Market Potential for Region II*

System Cost ($/sq ft)	9	15	20
($/m^2)	97	161	215
Optimum Area (sq ft/person)	12	6	2.5
(m^2/person)	1.11	0.56	0.24
Solar Energy Contribution (%)	71	44	19
Savings ($/person)	80	26	5
Savings (barrels fuel/person)	12.4	7.7	4.0
Market Potential (sq ft x 10^6)	1.3	0.65	0.27
(m^2 x 10^5)	1.2	0.60	0.25
(for entire region 108,000 personnel)			
Potential Dollar Savings (millions)	8.6	2.8	0.5
Potential Fuel Savings (million barrels)	1.3	0.8	0.4
Break-Even Area (sq ft/person)	22.5	12.5	5.0
(m^2/person)	2.00	1.16	0.46
Solar Energy Contribution (%)	86	72	36
Savings (barrels/person)	15.0	12.6	6.3
Market Potential (sq ft x 10^6)	2.43	1.35	0.54
(m^2 x 10^5)	2.26	1.25	0.50
(for entire region 108,000 personnel)			
Potential Fuel Savings (million barrels)	1.6	1.4	0.7

*Figures based on a 20-year life.

Table 6
Market Potential for Region III*

System Cost ($/sq ft)	9	15	20
($/m^2)	97	161	215
Optimum Area (sq ft/person)	12	6	2
(m^2/person)	1.11	0.56	0.19
Solar Energy Contribution (%)	67	42	16
Savings ($/person)	70	20	5
Savings (barrels fuel/person)	11.7	7.3	2.8
Market Potential (sq ft x 10^6)	1.18	0.59	0.20
(m^2 x 10^5)	1.10	0.56	0.19
(for entire region 98,000 personnel)			
Potential Dollar Savings (millions)	6.8	1.9	0.5
Potential Fuel Savings (million barrels)	1.1	0.7	0.5
Break-Even Area (sq ft/person)	21.3	12	4
(m^2/person)	1.98	1.11	0.38
Solar Energy Contribution (%)	84	67	29
Savings (barrels/person)	14.7	11.7	5.1
Market Potential (sq ft x 10^6)	2.09	1.18	0.39
(m^2 x 10^5)	1.94	1.10	0.36
(for entire region 98,000 personnel)			
Potential Fuel Savings (million barrels)	1.4	1.1	0.5

*Figures based on a 20-year life.

Table 7
Market Potential for Region IV*

System Cost ($/sq ft)	9	15	20
($/m^2)	97	161	215
Optimum Area (sq ft/person)	10.5	5	1.5
(m^2/person)	0.98	0.46	0.14
Solar Energy Contribution (%)	65	36	12
Savings ($/person)	65	18	4
Savings (barrels fuel/person)	11.3	6.3	2.1
Market Potential (sq ft x 10^6)	0.66	0.32	0.10
(m^2 x 10^5)	0.61	0.30	0.09
(for entire region 63,000 personnel)			
Potential Dollar Savings (millions)	4.1	1.1	0.3
Potential Fuel Savings (million barrels)	0.7	0.4	0.15
Break-Even Area (sq ft/person)	22	10.5	3
(m^2/person)	2.04	0.98	0.28
Solar Energy Contribution (%)	85	65	23
Savings (barrels/person)	14.8	11.3	4.0
Market Potential (sq ft x 10^6)	1.39	0.66	0.19
(m^2 x 10^5)	1.29	0.61	0.18
(for entire region 63,000 personnel)			
Potential Fuel Savings (million barrels)	0.9	0.7	0.3

*Figures based on a 20-year life.

Table 8
Total Market Potential*

System Cost ($/sq ft)	9	15	20
($/m^2)	97	161	215
Optimum Area			
Market Potential (sq ft x 10^6)	4.40	2.32	0.89
(m^2 x 10^5)	4.11	2.17	0.83
(for entire region 377,000 personnel)			
Potential Dollar Savings (millions)	29.2	9.6	2.4
Potential Fuel Savings (million barrels)	4.5	2.9	1.5
Break-Even Area			
Market Potential (sq ft x 10^6)	8.55	4.76	1.82
(m^2 x 10^5)	7.94	4.42	1.69
(for entire region 377,000 personnel)			
Potential Fuel Savings (million barrels)	5.6	4.7	2.4

*Figures based on a 20-year life.

4 CONCLUSIONS

1. Solar domestic hot water heating systems using flat-plate collectors are economically justifiable for DOD barracks. Individual analysis of the solar system at a particular location is necessary, however, to obtain the proper mix of solar and conventional systems, thus optimizing the economic savings.

2. The universal curve for solar hot water heating presented in Appendix A is a good first approximation of the solar potential and is valid for all locations.

3. Roofs on existing DOD barracks have sufficient space and in most instances are flat enough to easily accommodate solar collectors for domestic hot water heating purposes.

4. Solar domestic hot water systems provide greatest solar utilization when the total storage volume is roughly equivalent to 1 day's usage and the solar collectors are tilted to the latitude of the location.

5. Although the market potential curve for solar domestic water heating in DOD barracks can provide preliminary planning guidance, individual building assessments are required to determine the optimum economic area of collectors for a particular location.

6. The market potential for solar domestic hot water heaters is very sensitive to system costs.

7. The solar collector market potential for DOD barracks at a future system cost of \$9/sq ft (\$97/m^2) is approximately 4.4 million sq ft (409 000 m^2). Application of this collector area could, over a 20-year life, save 4.5 million barrels of fuel and an estimated \$29 million.

8. The greatest potential for solar utilization is in the southwest (Region I). Initial solar domestic hot water heater applications will provide the earliest payback in this region.

5 RECOMMENDATIONS

1. FEA should initiate planning to provide a common method that Government facility managers, including those in DOD, can use to assess their facilities' potential for solar energy utilization.

2. DOD should initiate planning to provide a method facility managers can use to perform a preliminary assessment of the solar domestic hot water heating potential of each barracks under their control and report findings for consolidation at a central point.

3. Several barracks throughout the United States should be selected for measurement of actual domestic hot water usage to provide data on actual typical consumption and daily usage demand profile.

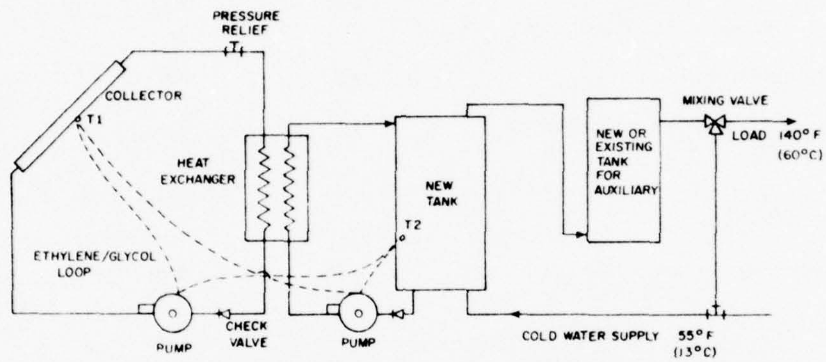


Figure 1. Hot water system simulation model for BEQ/BOQ.

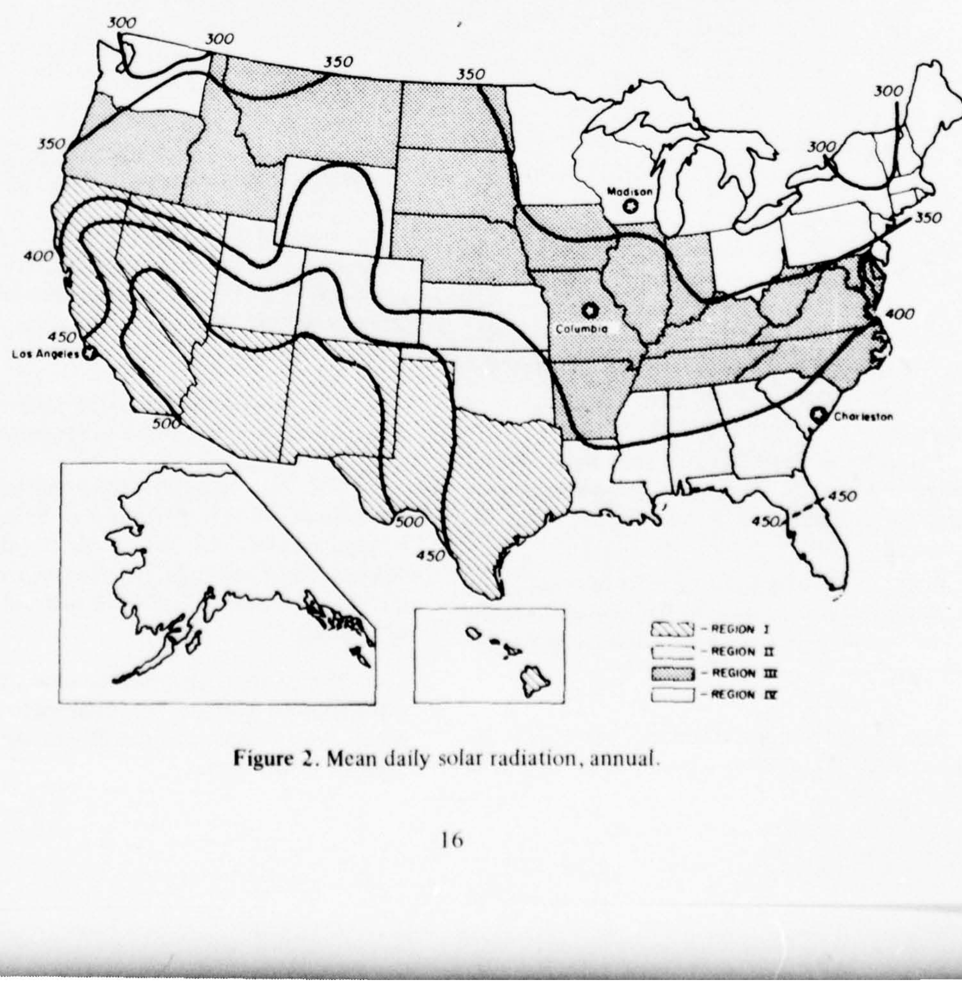


Figure 2. Mean daily solar radiation, annual.

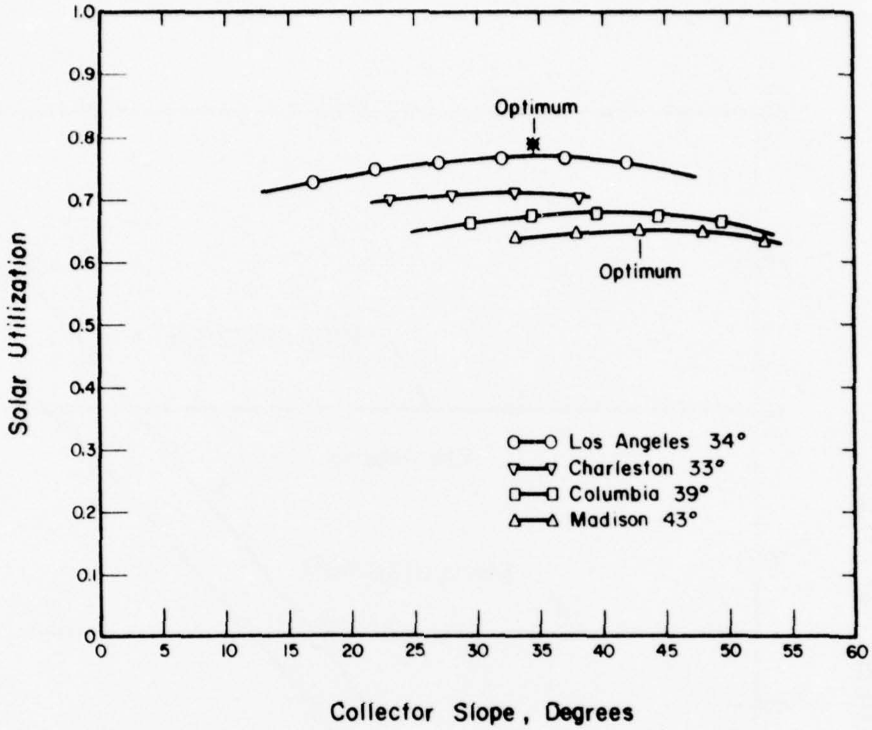


Figure 3. Effect of Collector Slope on fraction of load met.

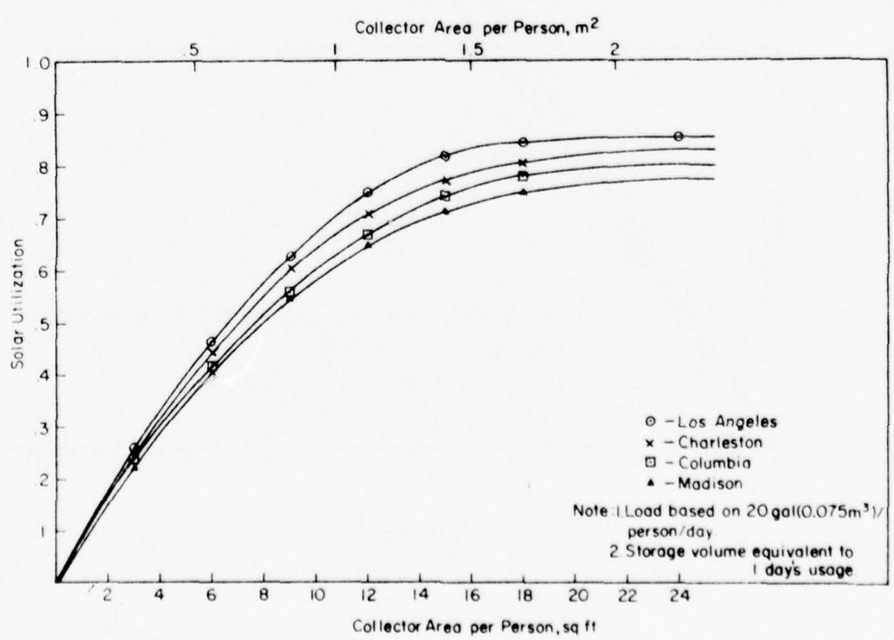


Figure 4. Collector area vs solar utilization.

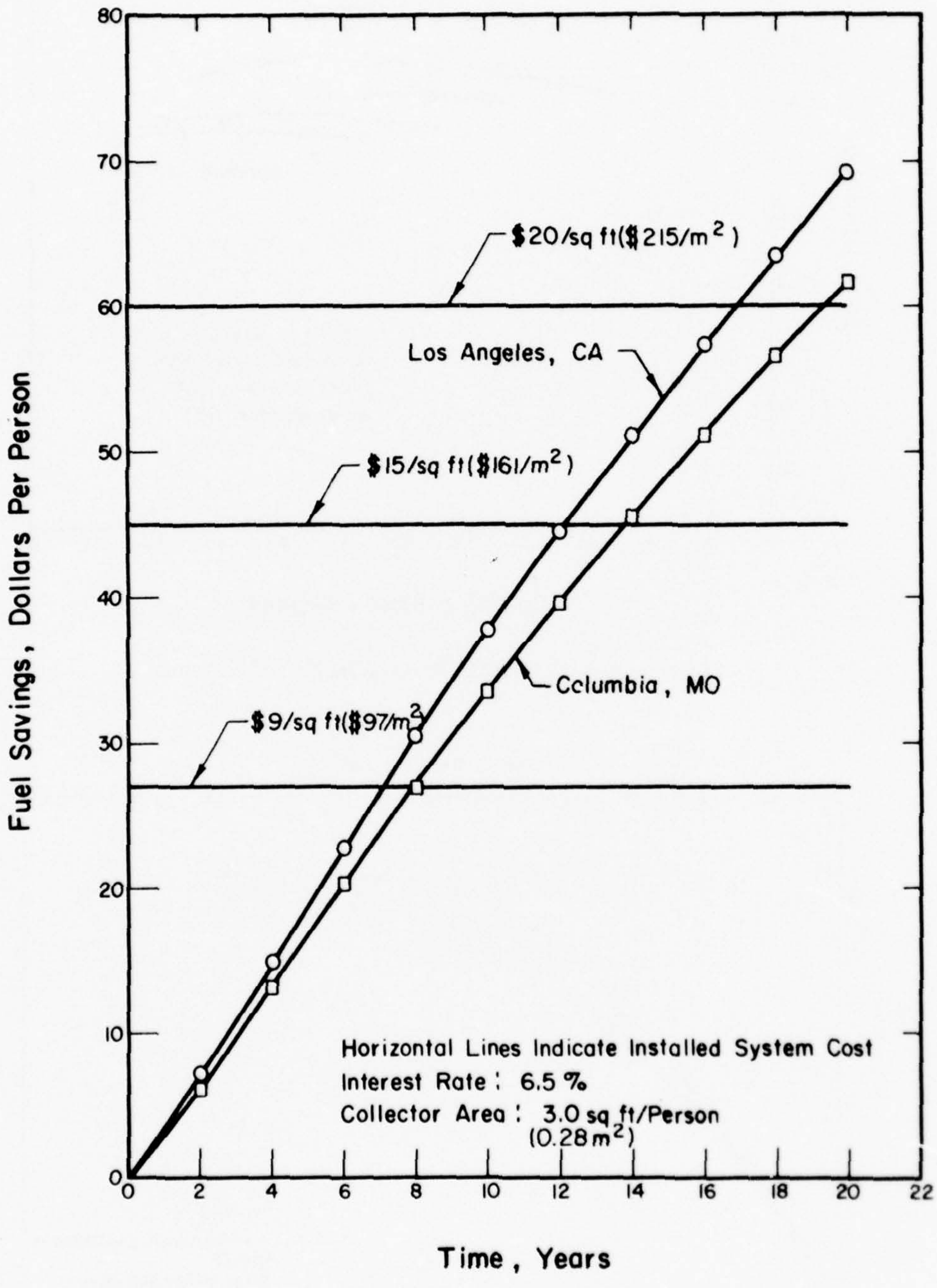


Figure 5. Life-cycle fuel savings for Los Angeles, CA, and Columbia, MO (collector area = 3.0 sq ft/person).

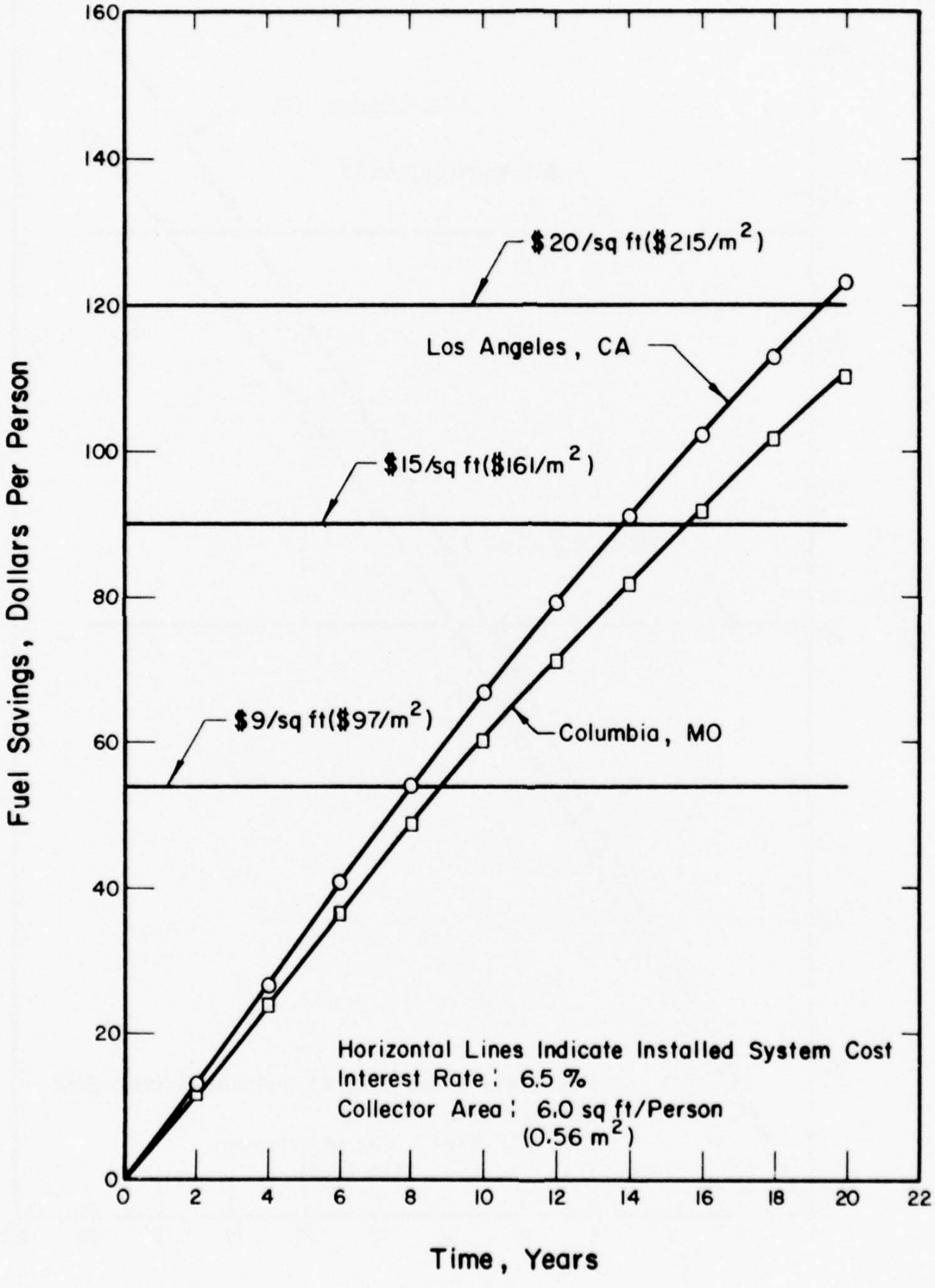


Figure 6. Life-cycle fuel savings for Los Angeles, CA, and Columbia, MO (collector area = 6.0 sq ft/person).

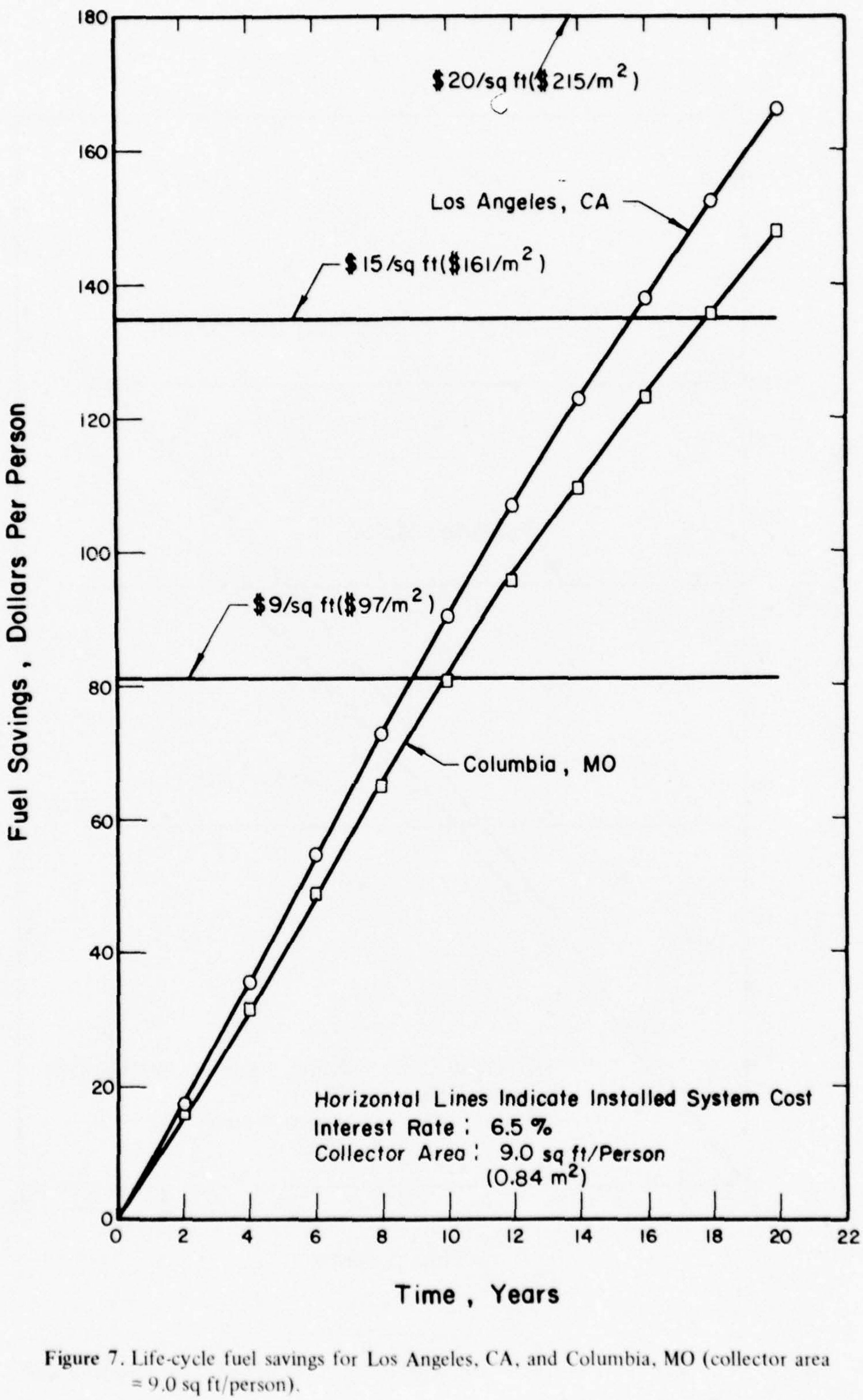


Figure 7. Life-cycle fuel savings for Los Angeles, CA, and Columbia, MO (collector area = 9.0 sq ft/person).

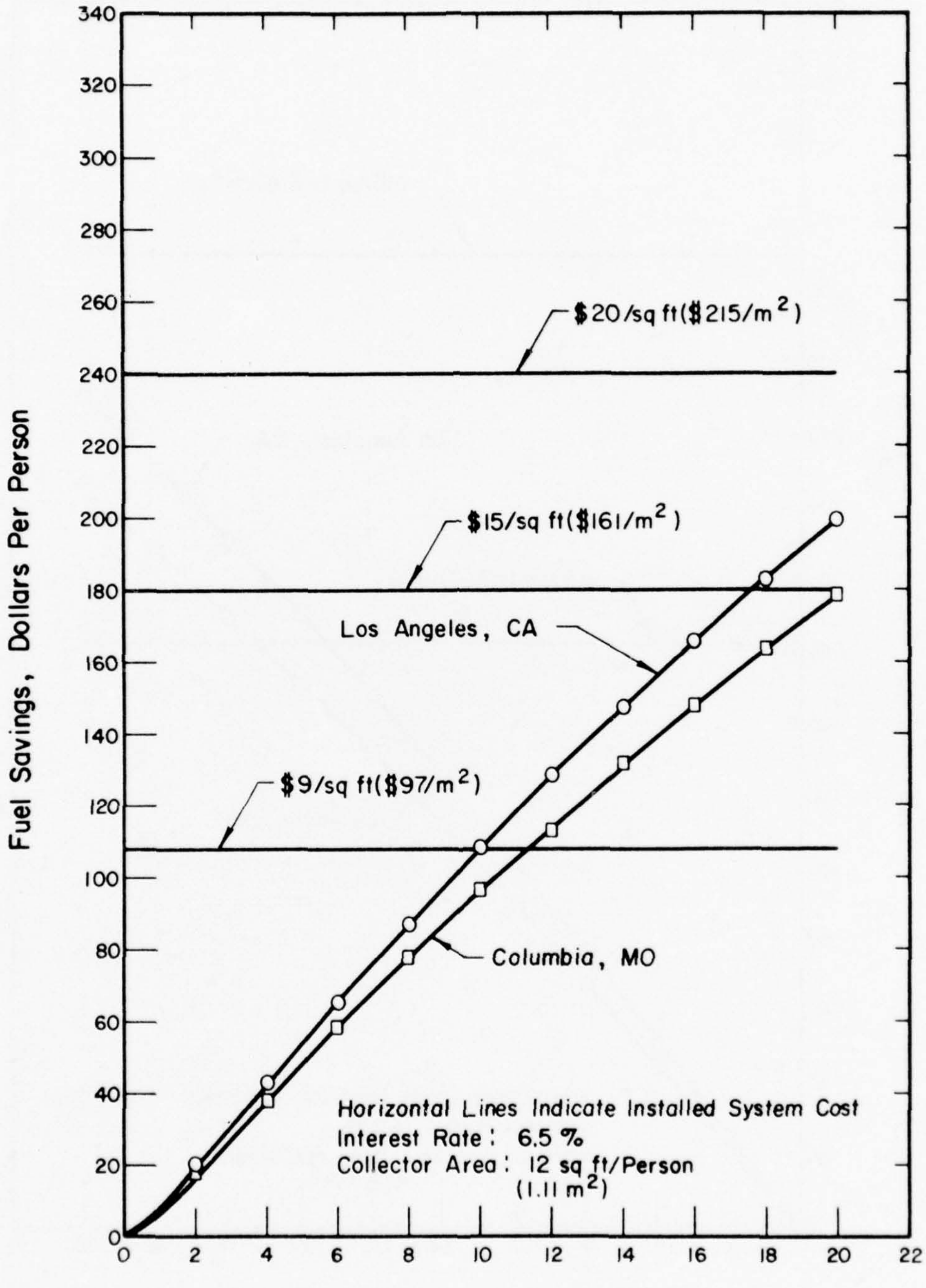


Figure 8. Life-cycle fuel savings for Los Angeles, CA, and Columbia, MO (collector area = 12.0 sq ft/person).

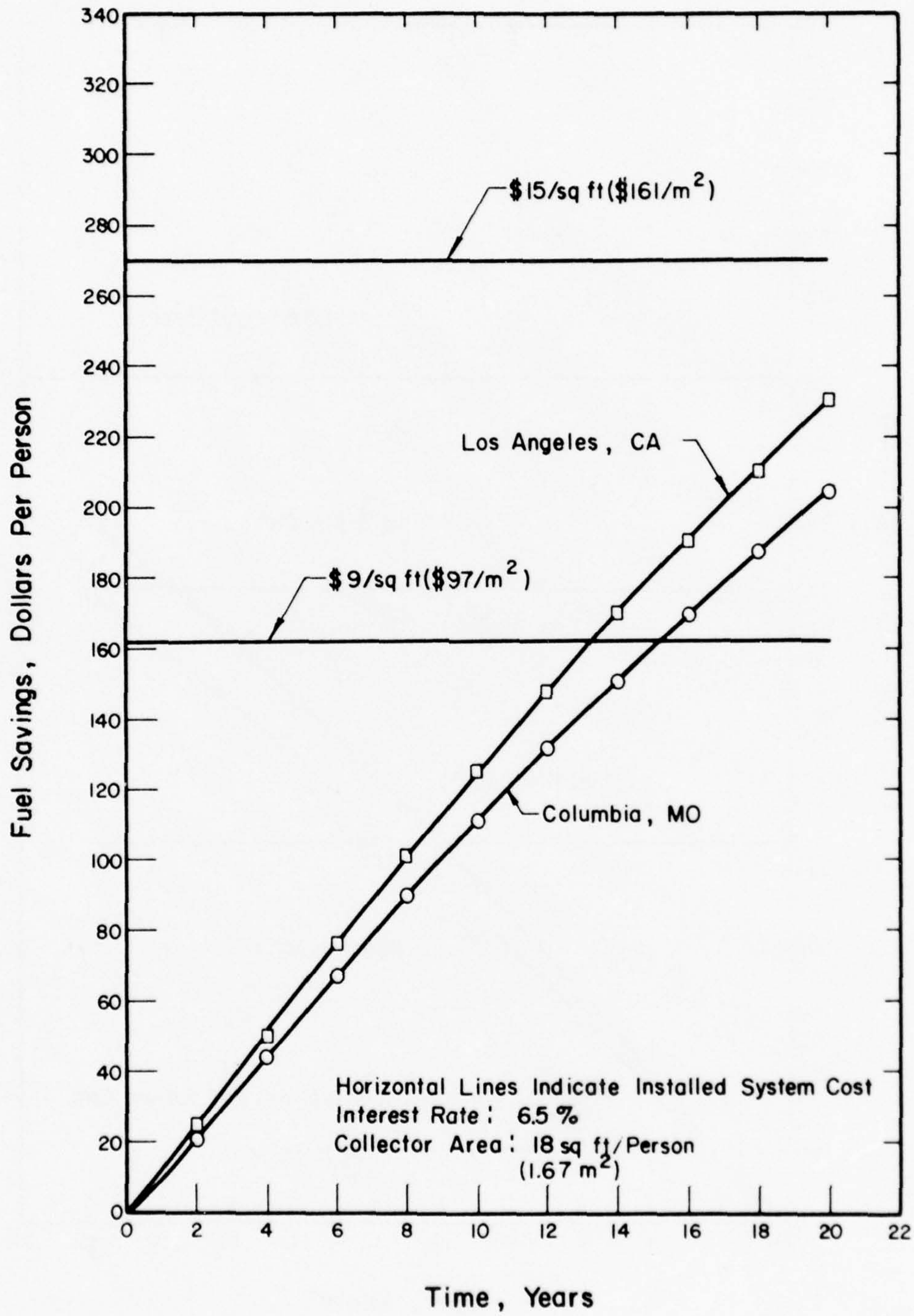


Figure 9. Life-cycle fuel savings for Los Angeles, CA, and Columbia, MO (collector area = 18.0 sq ft/person).

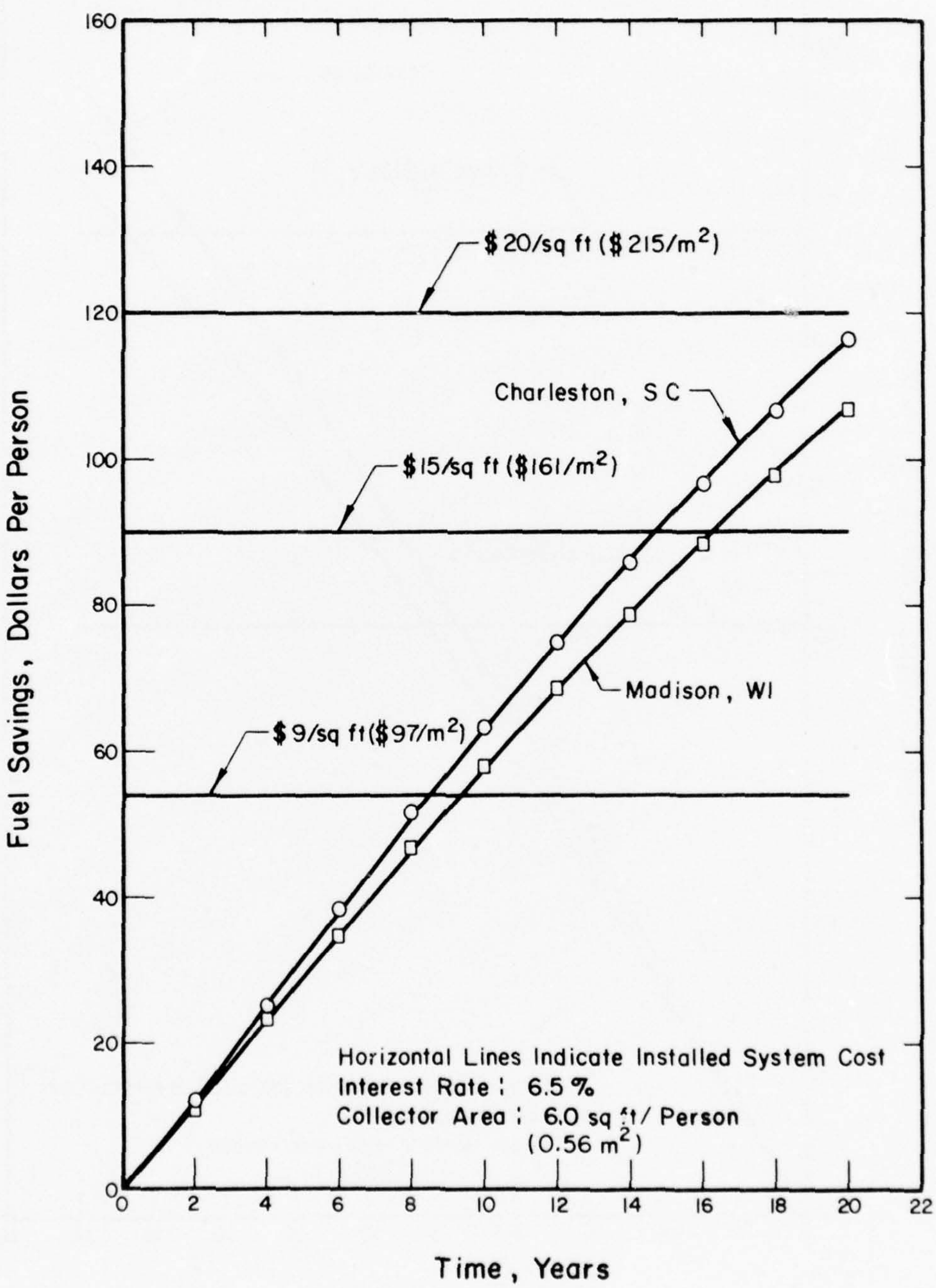


Figure 10. Life-cycle fuel savings for Charleston, SC, and Madison, WI (collector area = 6.0 sq ft/person).

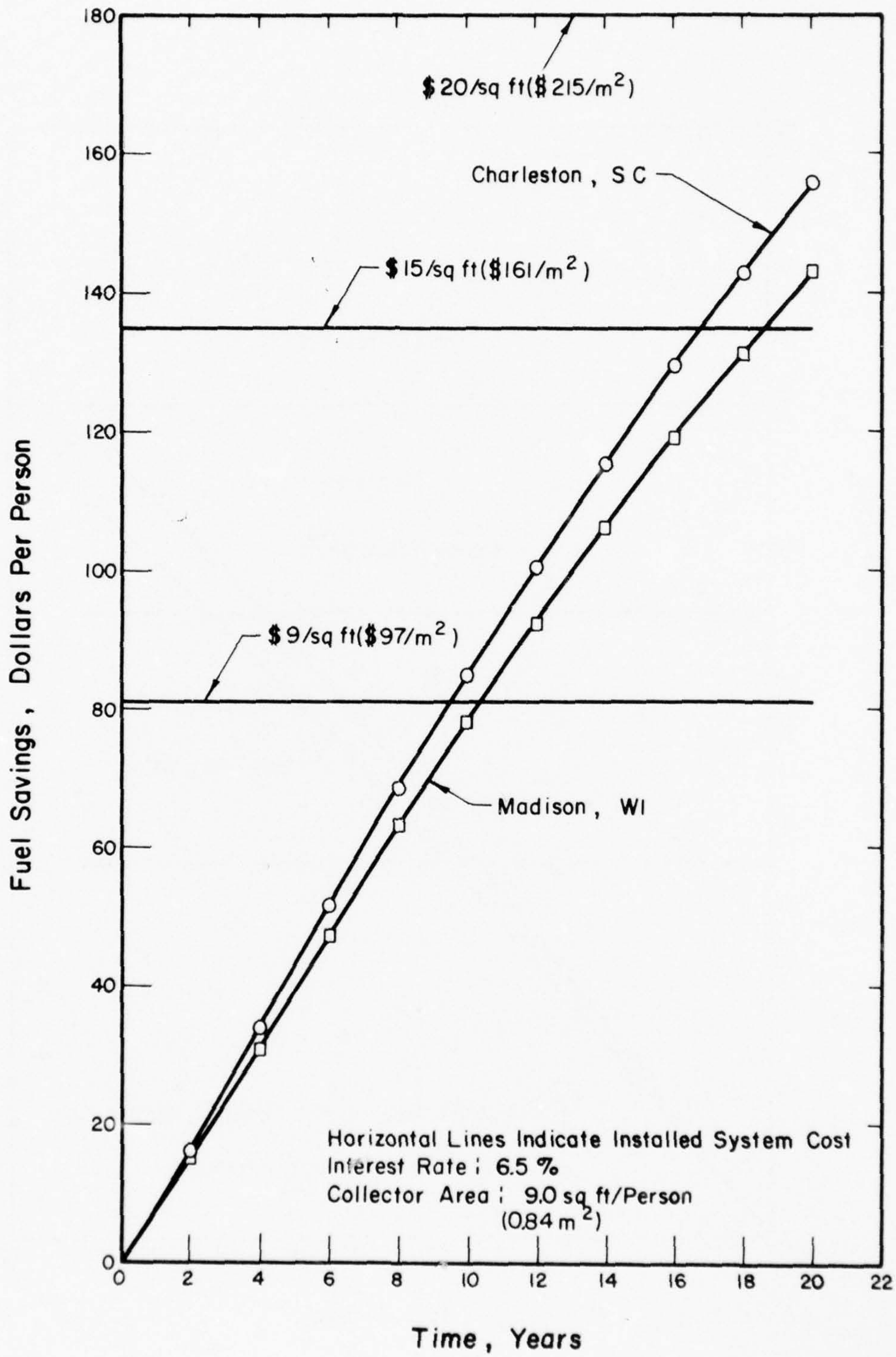


Figure 11. Life-cycle fuel savings for Charleston, SC, and Madison, WI (collector area = 9.0 sq ft/person).

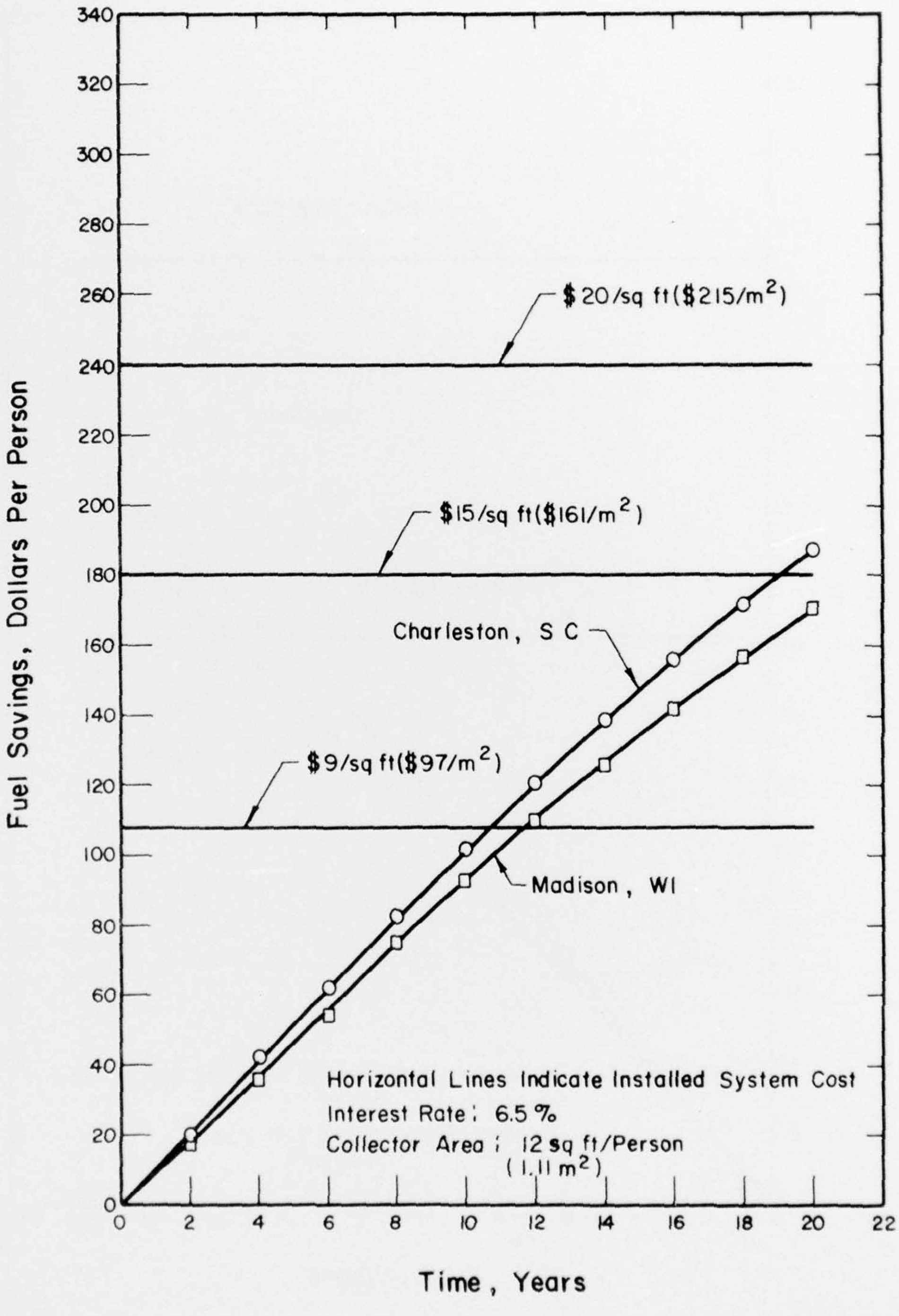


Figure 12. Life-cycle fuel savings for Charleston, SC, and Madison, WI (collector area = 12.0 sq ft/person).

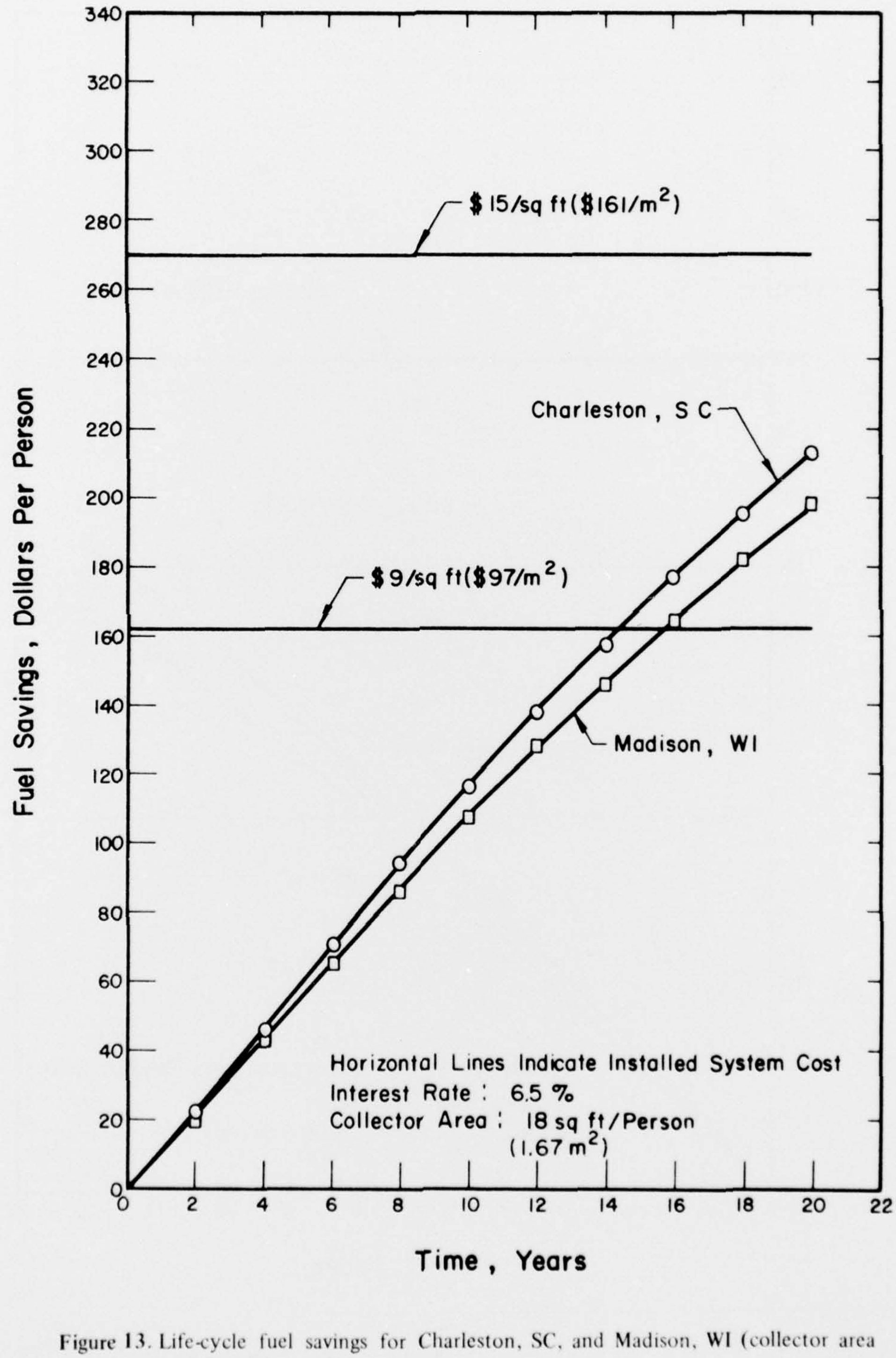


Figure 13. Life-cycle fuel savings for Charleston, SC, and Madison, WI (collector area =18.0 sq ft/person).

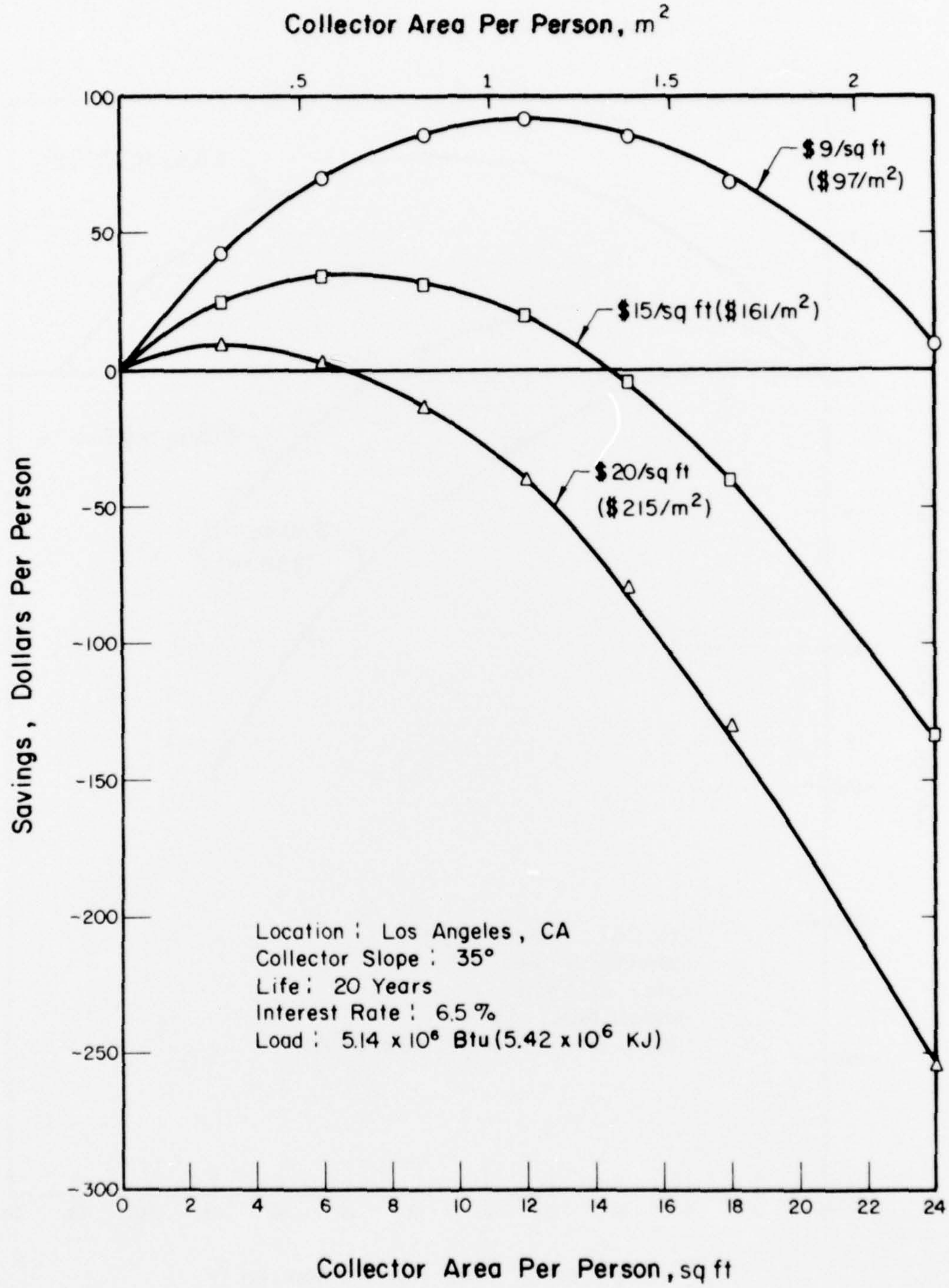


Figure 14. Life-cycle fuel savings as a function of collector area—Los Angeles, CA.

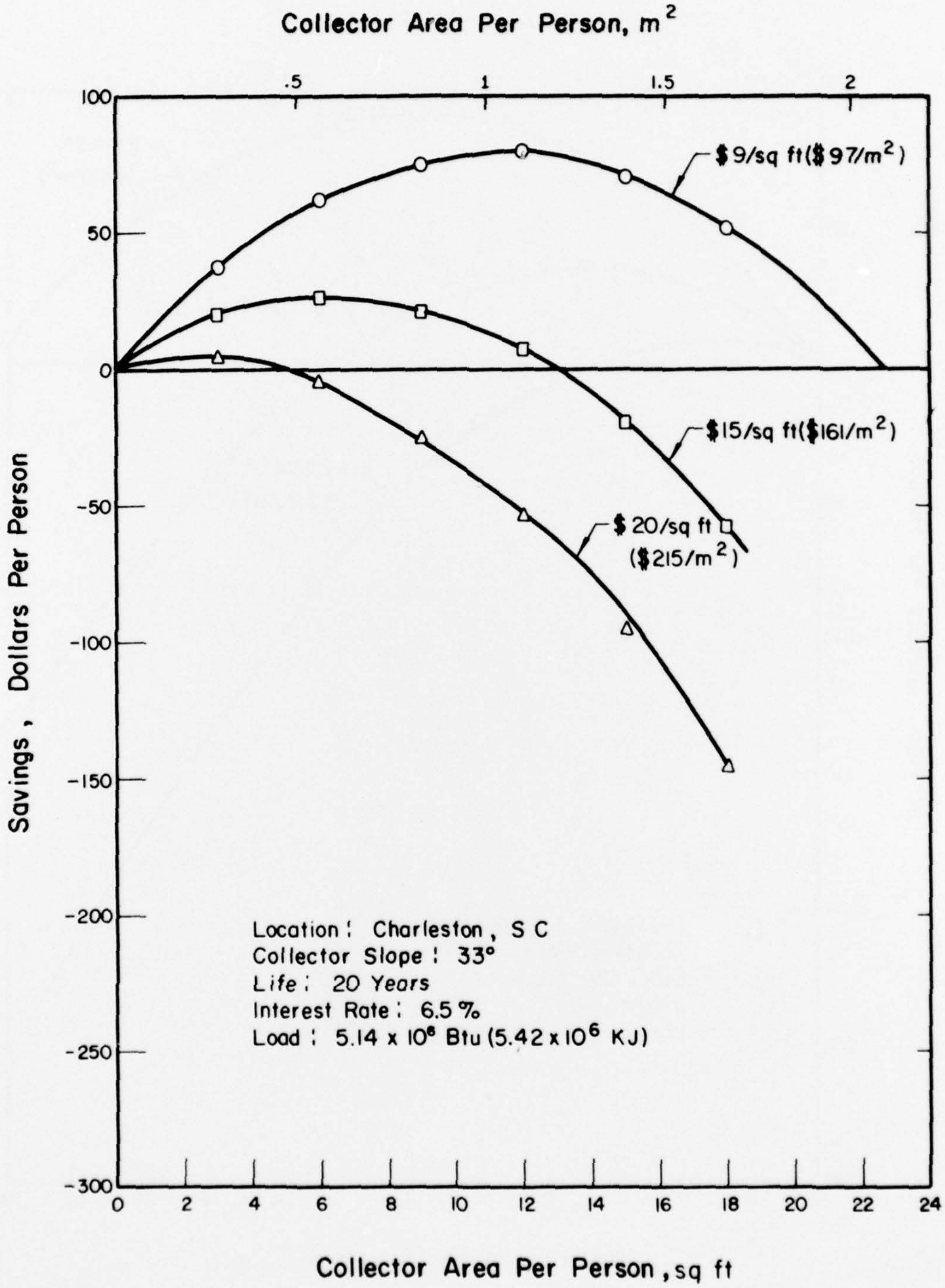


Figure 15. Life-cycle fuel savings as a function of collector area–Charleston, SC.

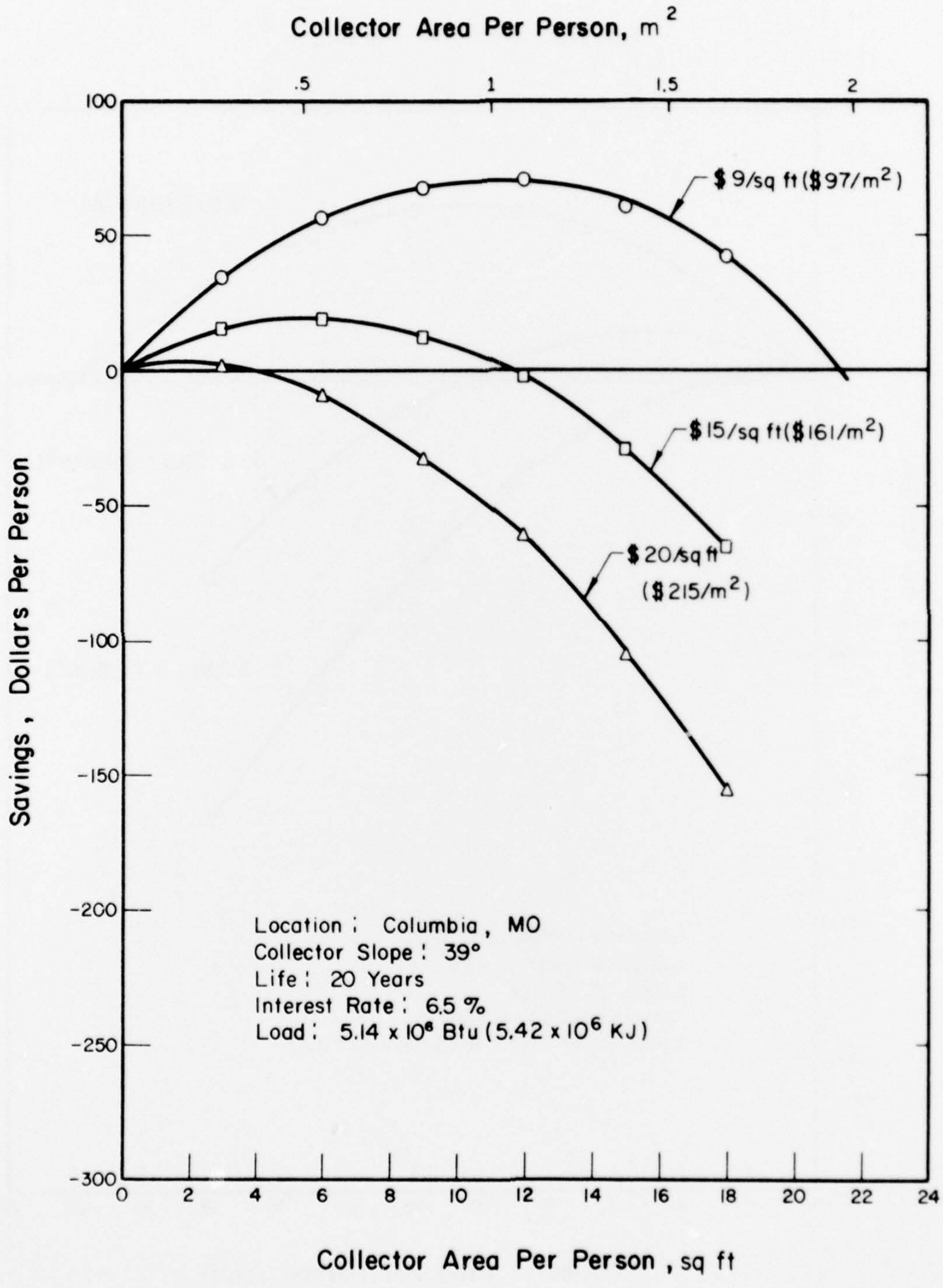


Figure 16. Life-cycle fuel savings as a function of collector area–Columbia, MO.

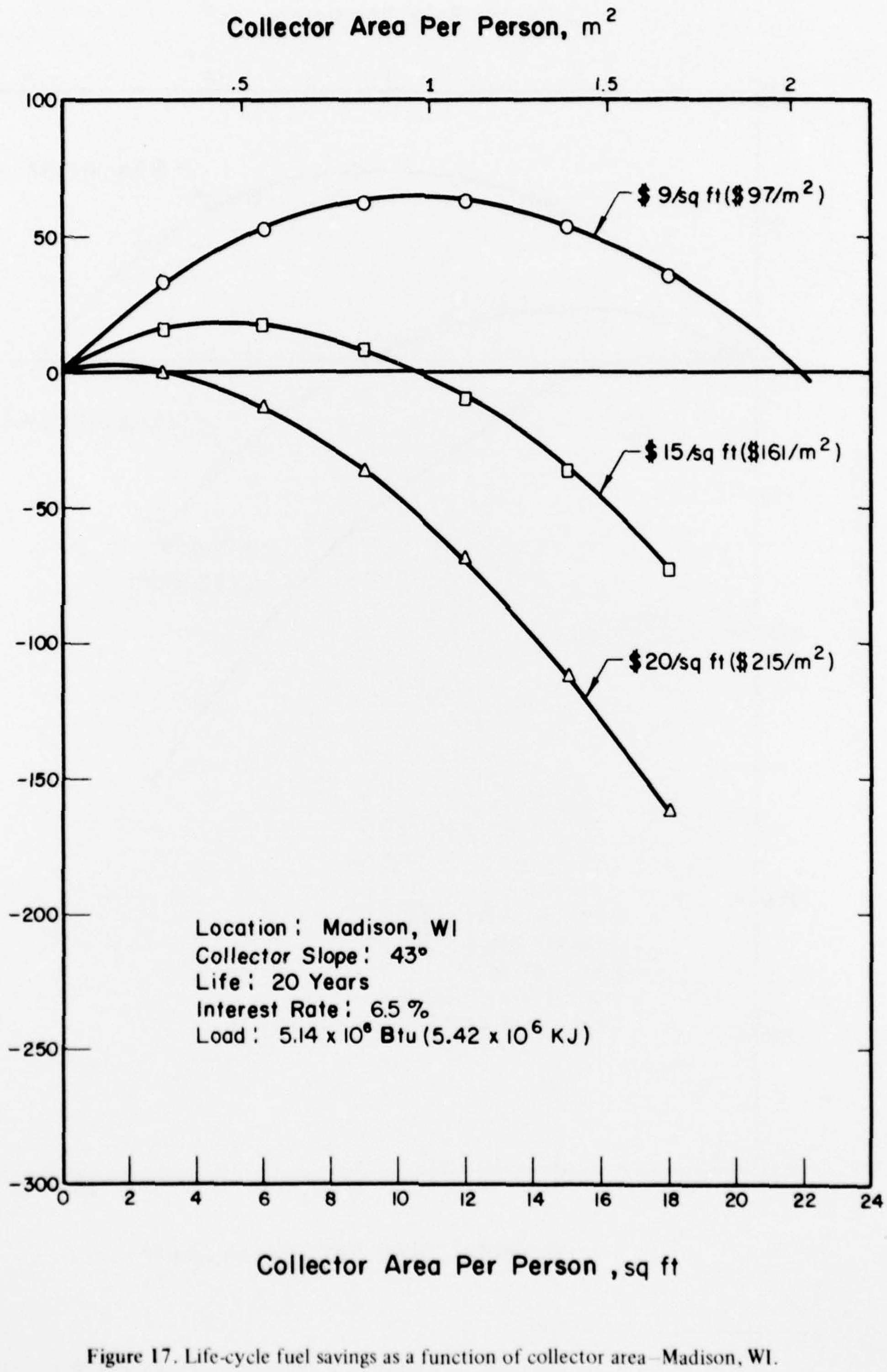


Figure 17. Life-cycle fuel savings as a function of collector area—Madison, WI.

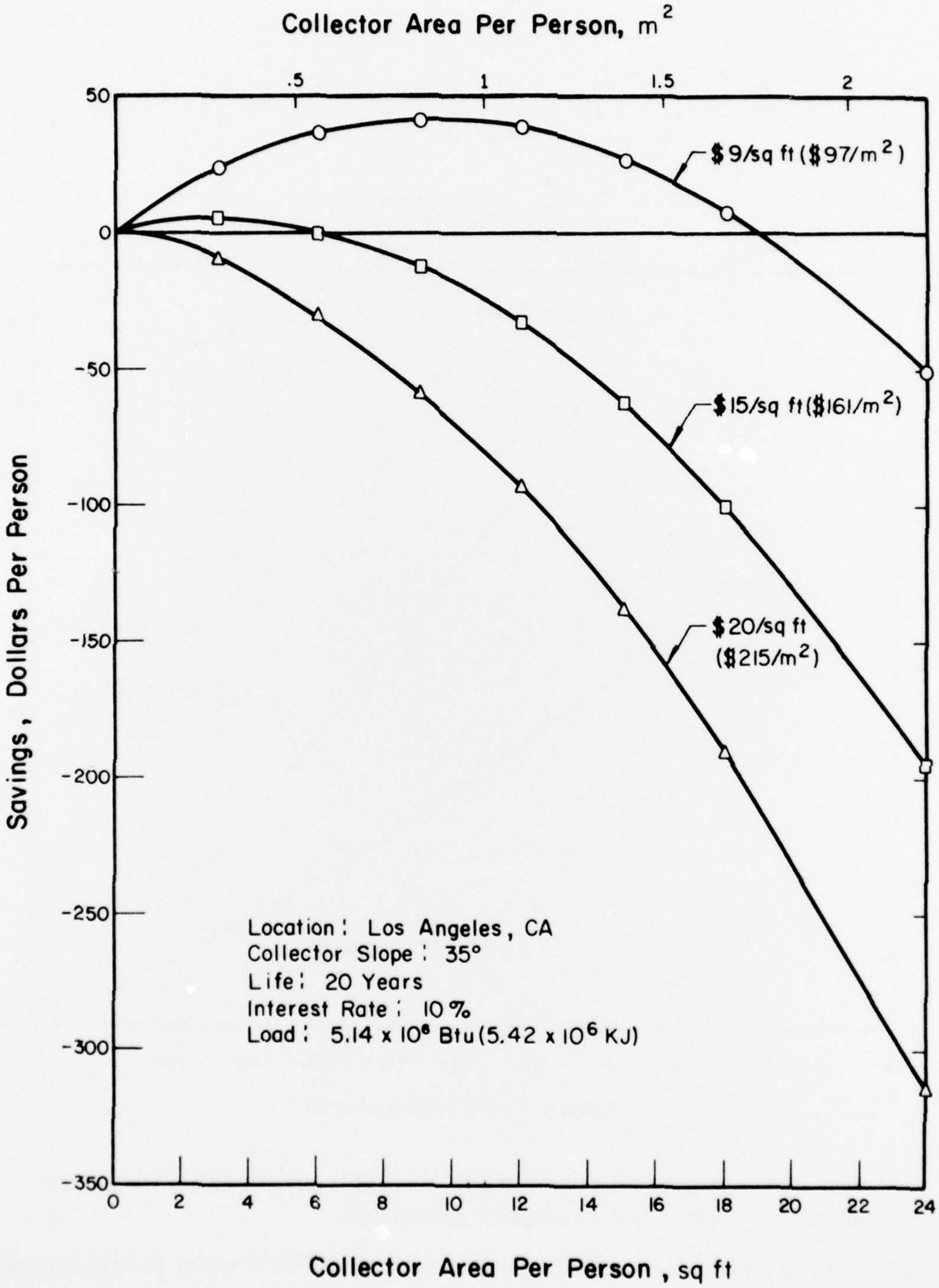
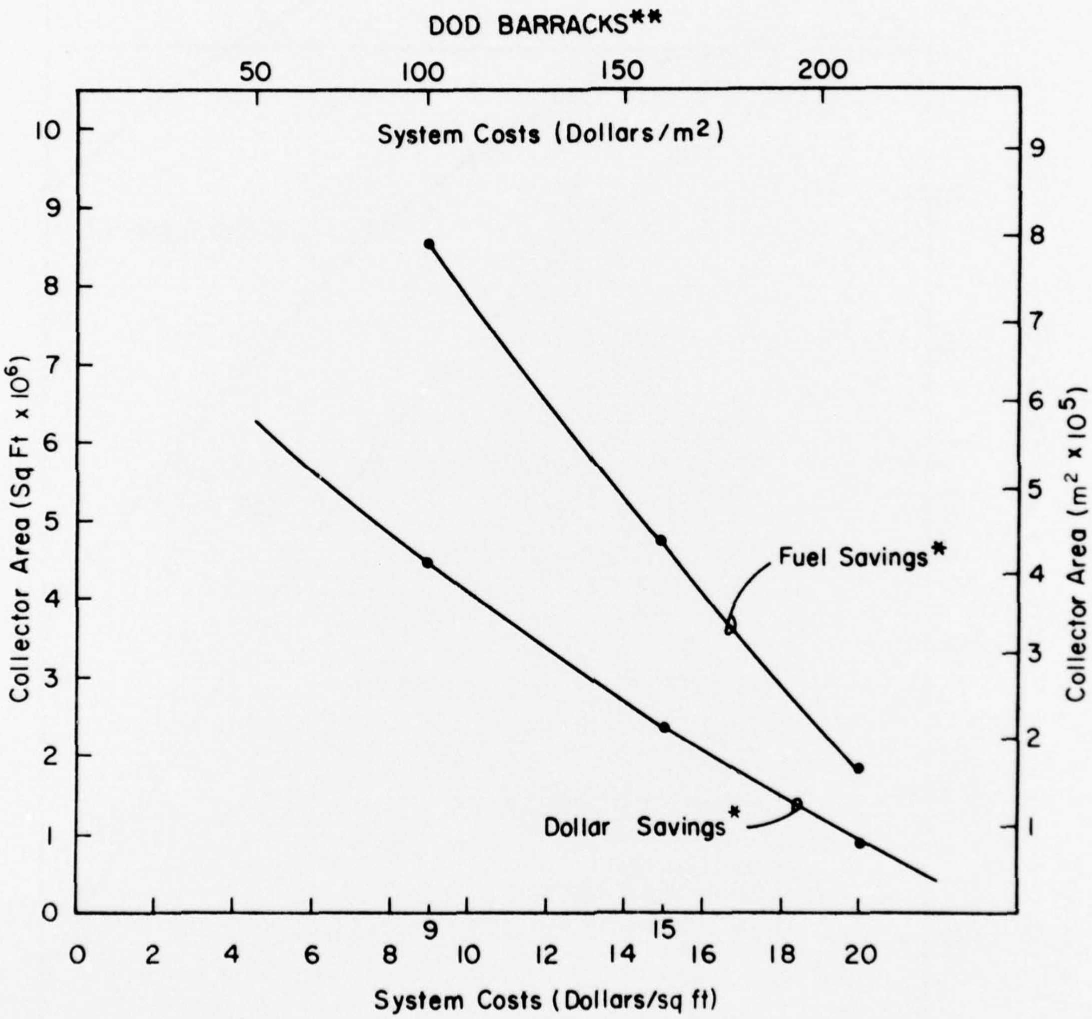


Figure 18. Life-cycle fuel savings based on 10 percent interest rate.



*Lower curve represents market if dollar savings is paramount. Upper curve indicates market if fuel savings is paramount.

**Based on estimated load of 20 gal (0.075m²) of 140°F water per person per day.

Figure 19. Solar hot water heating system costs vs probable market penetration.

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APPENDIX A:

UNIVERSAL CURVE FOR HOT WATER HEATING

Derivation and Use

The universal curve for hot water heating (Figure A1), which was developed from computer simulation of the system shown in Figure 1, can be used to estimate the solar collector area required to satisfy a given percentage of hot water heating load for any location. The simulation was accomplished for four geographic/climatic locations: Los Angeles, CA; Charleston, SC; Columbia, MO; and Madison, WI. The data points shown on the curve were generated using computer simulations of the system at a storage volume equivalent to 1 day's usage, since this storage volume was found to optimize use of solar energy for hot water heating purposes.

The simulations were run using a single-cover flat-plate collector with a selective surface. However, use of the curve can be expanded to include other collector types. Table A1 shows the results of research performed at CERL in which several different collector designs were simulated holding other system parameters constant. The table provides a multiplier that can be used to find the required collector area should a different design be chosen.

To illustrate use of the table, if a collector with the same selective surface is used but is fitted with two glass covers, the collector area determined from the universal curve would be multiplied by 0.93. If a single cover, nonselective collector is chosen (absorptivity and emissivity = 0.96), the area would be multiplied by 1.55.

It can be seen that the curve fits the data points remarkably well (i.e., ± 5 percent difference on the vertical scale). The data points are shown in a legend so closer approximations of the solar utilization can be made depending on the user's location.

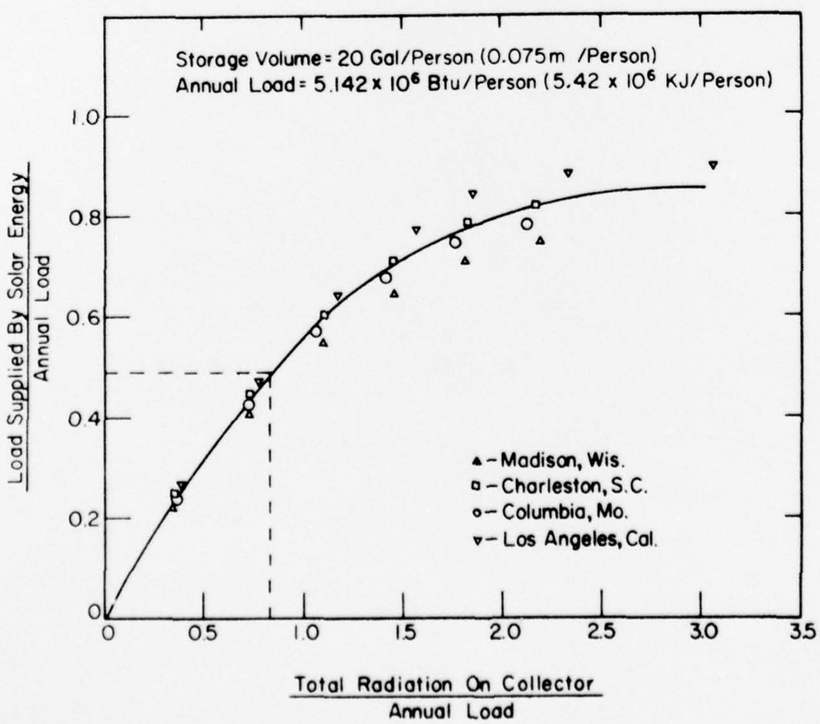

Figure A1. Universal curve for hot water heating with solar energy.

Table A1
Collector Factors

	Non-Selective Collector	Semi-Selective Collector	Selective* Collector
Absorptivity of Plate	0.96	0.94	0.90
Emissivity of Plate	0.96	0.30	0.10
One Glass Cover**	1.55	1.09	1
Two Glass Covers	1.09	0.97	0.93

* A selective collector was used in developing the curve.
**Transmittance of each glass cover was 0.09.

Example

The following information and example explains the use of the universal curve. Topeka, KS, was the location used in the example.

1. Basic Data Required:

Location chosen	=	Topeka, KS
Mean daily horizontal radiation (available from National Weather Service)	=	380 langleys
Hot water consumption (per person per day)	=	30 gal (0.11 m^3)
Entering cold water temperature	=	45°F (7°C)
Leaving water temperature	=	140°F (60°C)
Optimum collector tilt angle (equivalent to location latitude)	=	39°
Latitude	=	39°
1 Langley (conversion to Btu/sq ft)	=	3.6 Btu/sq ft (40.8 kJ/m^2)

2. Load Calculation:

Annual Load = 30 gal x 8.33 lb/gal x (140°F − 44°F) x 365 days

Annual Load = 8.67×10^6 Btu/person (9.15×10^6 kJ/person)

3. The solar radiation incident on tilted collector surface is determined by the following equation:

$$\theta_c\text{RAD} = \frac{\text{COS}(\theta_l - 7 - \theta_c) \times \text{HRAD}}{\text{COS}(\theta_c - 7)} \qquad \text{[Eq A1]}$$

where:

θ_cRAD = radiation on tilted surface (Btu/sq ft)
HRAD = horizontal radiation (Btu/sq ft)
θ_l = latitude in degrees
θ_c = optimum tilt angle in degrees (equivalent to location latitude)

$$\theta_c\text{RAD} = \frac{\text{COS}(39° - 7° - 39°) \times 380 \text{ langleys} \times 3.6 \times 365 \text{ days}}{\text{COS}(39° - 7°)}$$

θ_cRAD = 5.84×10^5 Btu/sq ft (6.62×10^6 kJ/m^2)

4. The percent of load supplied by solar energy can be determined using the universal curve (Figure A1).

a. Assuming a collector area of 12 sq ft (1.11 m^2) per person

$$\frac{\text{Total Radiation on Collector}}{\text{Annual Load}} = \frac{\theta_c\text{RAD} \times \text{sq ft}}{\text{Annual Load}}$$

$$= \frac{5.84 \times 10^5 \times 12 \text{ sq ft}}{8.67 \times 10^6} = .808 \qquad \text{[Eq A2]}$$

From the curve, .808 corresponds to 48 percent of the load supplied by solar energy.

b. Assuming a collector area of 18 sq ft (1.67 m^2) per person

$$\frac{5.84 \times 10^5 \times 18 \text{ sq ft}}{8.67 \times 10^6} = 1.21$$

From the curve, 1.21 corresponds to 63 percent of the load.

c. To provide a certain percentage of the load with solar energy, the equation can be worked as follows:

Select the percentage load desired: in this example 30 percent was chosen. Find the corresponding point on the radiation ordinate and solve for the area (called "Z" in this example).

$$\frac{5.84 \times 10^5 \; 5 \times \text{"Z"}}{8.67 \times 10^6} = .49$$

$$Z = 7.4 \text{ sq ft } (0.69 \text{ m}^2)$$

Thus, 7.4 sq ft (0.69 m^2) of collector area per person will provide 30 percent of the load.

APPENDIX B: DEMAND/CONSUMPTION METHOD*

Table B1 defines the variables used in calculating water demand and consumption.

Table B1
Definition of Variables

Type of Building	A	B	C	D
BEQ w/mess	40 (0.15)	14	7	5.71
BEQ wo/mess	30 (0.11)	14	6	5.00
BOQ	40 (0.15)	8	4	10.00

A = gallons (m^3) per person per day at 140°F (60°C).
B = duration of average heating period, hours/day.
C = duration of peak load, hours/day.
D = peak load factor.
N = number of people.

Water heater capacity is calculated according to

$$\text{Heating Capacity (gal/hr)} = \frac{A \times N}{B} \qquad \text{[Eq B1]}$$

Storage capacity is calculated by

Storage Capacity (gal)

$$= \text{Heating Capacity} \times \frac{(B - C)}{(.75 \times C)} \qquad \text{[Eq B2]}$$

The 0.75 factor is used because only 75 percent of the water in the storage tank is assumed to be hot enough for satisfactory use.

*From *Plumbing*, TM 5-810-5 (Department of the Army, May 1972).

TM 5-810-5 allows a designer some leeway in hot water system design. If a larger storage tank is used, the heating capacity can be reduced, and vice versa. Eq B3 can be solved for either the revised heating or storage capacities if a change is required for the other component.

$$\text{Storage Capacity (gal)} \times .75 + \text{Heating Capacity (gal/hr)} = D \times N \qquad \text{[Eq B3]}$$

Because the capacity of the water heater and storage tank can vary, there appear to be no standard hot water heaters or tanks employed in bachelor housing. TM 5-810-5 can be used, however, to estimate the capacities of the hot water heater.

APPENDIX C: ECONOMIC ANALYSIS EQUATIONS

An interest rate of 6.5 percent was used to evaluate the time value of money. The future fuel savings, based on present fuel oil costs of \$2.50/MBtu (\$2.39/GJ) escalated 10 percent for each of the first 4 years and 4 percent for the remaining years, were discounted to their present value using Eq C1:

$$P = S \frac{1}{(1 + i)^n} \qquad \text{[Eq C1]}$$

Where

P = present value
S = fuel savings, dollars
n = number of years
i = interest rate.

The cost of fuel was estimated for each of the 20 years (1976 – 1996) from Eq C2:

$$C_n = (C_{n-1})(R_n) \qquad \text{[Eq C2]}$$

Where
C_n = cost of fuel in year n
R_n = fuel escalation rate in year n.

The fuel savings were computed for each year based on the percent of load that could be satisfied by solar energy times the fuel cost for each year as determined in Eq C2. These figures were then summed to deter-

mine the present value of fuel savings through the life of the system.

Figures 5 through 18 show the results of this economic analysis. Figures 5 through 13 show the break-even points and payback period in years for a variety of collector areas at different geographical locations. The horizontal lines indicate the installed system costs for three different system life-cycle costs.

Curves were also generated for the net savings versus collector area per person (based on 20 gal [0.75 m^3] per day load) for each of the three system costs. The peaks of these curves indicate the collector area that is the most economically optimum (i.e., the greatest net dollar savings over a 20-year life). Points to the right of the curve produce greater fuel savings but lower actual dollar savings. The points where the curves cross the zero savings line are the collection areas that would result in recovery of the capital costs at the end of the 20-year payback period.

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